U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

N77-34044

A PREDICTION MODEL TO FORECAST THE COST IMPACT FROM A BREAK IN THE PRODUCTION SCHEDULE

Leon M. Delionback

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

September 1977

NASA TECHNICAL MEMORANDUM

NASA TM-78131

A PREDICTION MODEL TO FORECAST THE COST IMPACT FROM A BREAK IN THE PRODUCTION SCHEDULE

(NASA-TM-78131) A PREDICTION MODEL TO FORECAST THE COST IMPACT FROM A BREAK IN THE PRODUCTION SCHEDULE (NASA) 37 p HC A03/MF A01 CSCL 05C
N77-34044
Unclas
G3/83 49405

By Dr. Leon M. Delionback
Systems Analysis and Integration Laboratory

September 1977

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

NOTICE

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. NASA TM 78131	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE A Prediction Model to Forecast the Cost Impact from a Break in the Production Schedule		5. REPORT DATE September 1977
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Dr. Leon M. Delionback		8. PERFORMING ORGANIZATION REPORT #
9. PERFORMING ORGANIZATION NAME AND ADDRESS George C. Marshall Space Flight Center Marshall Space Flight Center, Alabama 35812		10. WORK UNIT NO.
		11. CONTRACT OR GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS National Aeronautics and Space Administration Washington, D.C. 20546		13. TYPE OF REPORT & PERIOD COVERED Technical Memorandum
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Prepared by Systems Analysis and Integration Laboratory, Science and Engineering

16. ABSTRACT

The losses which are experienced after a break or stoppage in sequence of a production cycle portends an extremely complex situation and involves numerous variables, some of uncertain quantity and quality. There are no discrete formulas to define the losses during a gap in production. The techniques which are employed are therefore related to a prediction or forecast of the losses that take place, based on the conditions which exist in the production environment. Such parameters as learning curve slope, number of predecessor units, and length of time the production sequence is halted are utilized in formulating a prediction model.

The pertinent current publications related to this subject are few in number, but are reviewed to provide an understanding of the problem.

Example problems are illustrated together with appropriate trend curves to show the approach. Solved problems are also given to show the application of the models to actual cases or production breaks in the real world.

17. KEY WORDS Production Break/Gap; Learning/Cost Improvement Curve; Figure of Merit; Prediction Model; Production Series; Characteristic Curve	18. DISTRIBUTION STATEMENT Unclassified — Unlimited

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified	37	NTIS

MSFC - Form 3292 (Rev December 1972)

For sale by National Technical Information Service, Springfield, Virginia 22151

ACKNOWLEDGMENTS

The author wishes to acknowledge the valuable assistance of Mr. James F. Patterson, EL43, and Mr. James P. Garner, EL02, in the preparation of this report.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

PREFACE

This analysis is concerned with the delay or stoppage brought about when a production system is halted after producing a number of units in a production series. When the learning process, as evidenced by the learning/cost improvement curve, is stopped whether for 1 month or 18 months, forgetting takes place, and retrogression back up the learning curve will take place. The amount or quantity of this retrogression will depend on a variety of different parameters.

The time series figure of merit approach is utilized to establish certain trend curves to explain the losses due to the process of forgetting. The construction of a prediction model is based on the values from the trend curves and is founded on a multiplicative time series type format.

After selection of suitable parameters for the trend curves, cuts are taken at suitable intervals and a characteristic curve is plotted. Interrogation of the characteristic curve is accomplished by entering the curve at a suitable figure of merit value. The resulting answer is expressed in terms of "percent of units lost due to forgetting." The answer is a prediction or forecast of the losses due to the forgetting process.

Considerable difficulty was experienced in acquiring suitable data points which would be useful in the actual model construction.

LIST OF TERMS AND DEFINITIONS

1. LEARNING/COST IMPROVEMENT CURVE

A learning/ cost improvement curve is a graphical plot on either cartesian or double logarithmic paper that represents the rate of learning progress by humans or some progressive innovation in the performance of some task or group of tasks. In general, these curves will approximate a decreasing exponential shaped curve, if the progress is normal. In the trade, the term "learning curve" has been used interchangeably with cost improvement curve, and will be so used in the text.

2. LOG LINEAR

This term is often used to describe learning/ cost improvement curves which are plotted on double logarithmic paper. In general, such curves appear as straight lines. This greatly simplifies determination of the slope and will make these curves easier to plot.

3. FACTOR

This term can be considered a synonym for parameter or feature when used in the text.

4. PARAMETER

A quantity or constant whose value varies with circumstances of its application.

5. FORGETTING CURVE

This term is used to express the reverse of a learning curve. As time passes with no learning, forgetting takes place. This activity when plotted will move in the opposite direction from a learning curve, but usually at the same slope.

6. FIGURE OF MERIT (FOM)

This term can be considered a numerical performance rating which is a measure of the relative performance of a system or design. The term is usually dimensionless, or is considered so in its applications to decision theory.

7. MODEL

A model is an approximation of reality which is frequently used to forecast or predict performance approximations of real world situations. Analytical models are sometimes referred to as math models, or as algorithms, which consist of a necessary and sufficient set of terms, values, and formulas needed to compute or predict an output value based on a known input or set of input values and recognized constraints or limitations.

8. SYSTEM

A system is a planned, integrated assembly or grouping such as hardware, software, and/or human elements which function together to produce some specific or unique desired effect or result. A subsystem is subordinate to a system, but must meet the same definition criteria.

9. TIME SERIES — TYPE STATISTIC

This number is a value artificially created by either multiplying a series of parameters times each other — $P_1 \times P_2 \times P_3 \times P_4$ or by adding the values $P_1 + P_2 + P_3 + P_4$. If the time element is excluded, the resulting number is called stationary. The resulting number or statistic is generally referred to as a figure of merit (FOM).

10. RETROGRESSION

This term is a synonym for the forgetting curve within the context of this publication.

11. PRODUCTION BREAK/GAP

These terms have been used to describe the situation when there is a pause or stoppage in the production series.

12. PRODUCTION SERIES

A term that is used to indicate a number of production assemblies being produced in a serial or consecutive manner.

TECHNICAL MEMORANDUM 78131

A PREDICTION MODEL TO FORECAST THE COST IMPACT FROM A BREAK IN THE PRODUCTION SCHEDULE

I. INTRODUCTION

The production break or gap is the state of affairs created when a production system is temporarily stopped after producing a specified number of units. The predecessor units quite frequently represent a series of research and development articles which are produced prior to the main or prime production run. To establish a basis for the analysis process, it is necessary to make certain assumptions or ground rules. One of the assumptions is that the tooling design is assumed to be unchanged, and the "production rate" is also assumed constant for purposes of analysis. Actually, it should not make any difference as to the consideration of the initial group of units, provided the conditions remain the same after the break (e.g., learning curve slope, tooling design, etc.). The solution methodology (model) will apply equally well to any other industry and will depend only on the acquisition of the appropriate data points. That is, the model is considered a general solution for the stated problem.

The methodology which is utilized is based on the statistical time series type analysis. Trend curves of the significant sensitive parameters are used to compute figure of merit (FOM) values which are used in the multiplicative time series format. Finally, a characteristic curve is plotted for the overall FOM to represent the entire production process for the production break. Figure 1 shows the steps in the development of the model.

An exhaustive search was made of the published information on production breaks. Although several articles were published on the general subject, few of the articles revealed information which could be used in the solution of an actual production break problem.

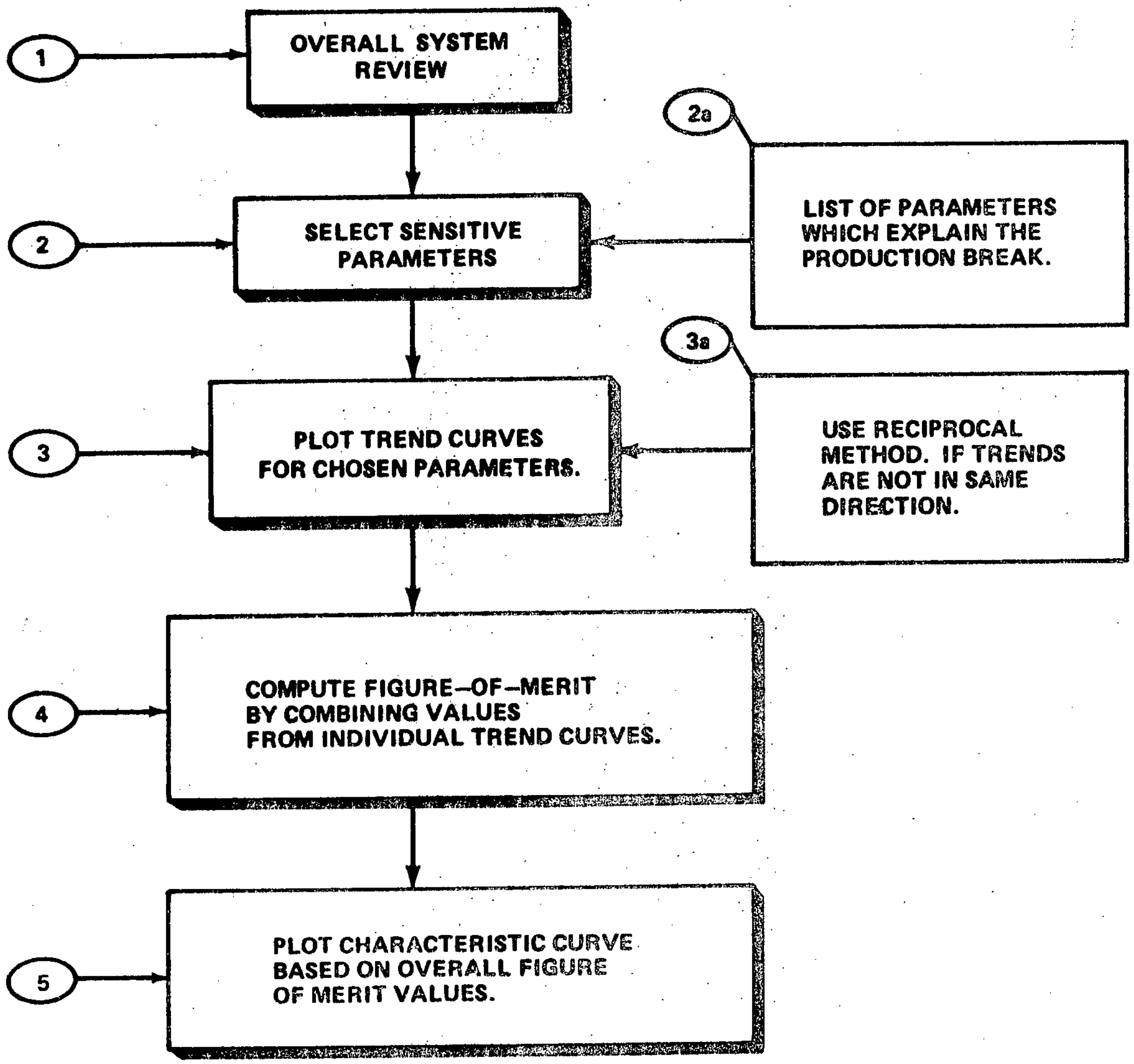


Figure 1. Procedure flow diagram for the development of prediction model.

A two-parameter and, finally, a three-parameter model were evolved to explain the losses resulting from a production break or gap. The three parameters which are believed to be significant and were used in constructing the model are: (a) length of time for the production break in months, (b) number of units in production sequence, and (c) slope of the learning curve for the units produced prior to break.

II. DISCUSSION OF THE CURRENT PUBLICATIONS AND RELATED INFORMATION

The most recent publication on the subject of production breaks is the one by J. G. Carlson [1]. The model which is presented here is based on a principle of "learning, forgetting, learning (LFL)" operations. This approach considers the learning which takes place on the prior units, but then as the retrogression of the production break takes place the process of forgetting follows. In a similar manner, the forgetting curve goes in the reverse direction at a slope either the same as the prior learning portion or at a different slope value. The forgetting curve begins at the point the production break begins and proceeds from that point. After the termination of the break the learning process will resume, and that portion of the model progresses from this point in time forward. Thus, the name of the model is fulfilled – LFL. As stated in Reference 1: "An interruption or forgetting interval expressed in weeks can easily be converted to equivalent units (lost) in a manner similar to that employed for the learning portion of the LFL (Learn, Forget, Learn) curve."

One valuable source of data used in the development of the prediction model was the book by E. B. Cochran [2]. Cochran, through analysis of the forgetting phenomenon in production operations, concludes that the quantity of forgetting after restart of the process is a function of (a) quantity of units which were produced, (b) the time interval of the interruption, and (c) the number of the original personnel that have been retained, as well as the status of the tooling design, methods, and/or support activities.

A source of information which proved to be very useful was the Boeing Company report published by J. Gauger [3]. Although no specific model or equation was given, a trend curve was shown which related the loss of learning to the time interval of the production break.

Another report [4] published by the Boeing Company related the production gap to a series of parameters which utilized various weightings for each aspect of the learning loss. This approach requires the acquisition of actual data points to apply. The parameters are as follows:

	Weights (%)
Production Personnel Learning	45.0
Supervisory Learning	15.0
Continuity of Production	20.0
Tooling	8.0
Methods	12.0
Total	100.0

This report also discusses the effect of a change in production rate on the overall production process. A report by G. Anderlohr [5] presents a similar approach.

A master thesis by A. A. Pichon [6] presents a model which is based on the regression analysis of data taken during production breaks in a machine shop environment. The model did not consider the length of the time interval of the production break or the number of production units involved in the process. These two aspects were considered to be essential in the development of a representative prediction model for the production break environment.

III. PREDICTION MODEL FORMULATION

Rather than a precise analysis based on the treatment of a well-founded group of details, this approach uses a methodology which is a proximate solution for the production break problem. The time-series multiplicative format [7] is utilized with a FOM system to gauge the various parameters. Trend curves based on three sensitive parameters are used to build a characteristic curve, which is the principal exhibit for the subject model. The characteristic curve is interrogated for each production break situation at conditions that are

determined by the parameters of the individual production breaks. The methodology is similar to techniques illustrated in previous publications [8-11]. The outputs from the subject model are the learning losses that are generated during the interval of the production break.

A. Trend Curve Relations

The choice of a particular variable to qualify as a parameter for the model is one that is governed, at least partially, by the availability of data. Initially it was reasoned that a model with a minimum of two parameters would be necessary to make a prediction of the quantity of learning loss; i.e., a two-parameter prediction model would be the result of this analysis. Trend curve data were determined to support the following two parameters: number of units in the production series prior to the break and length of time for the interval of the production break. Curves were plotted for the two parameters as in Figures 2 and 3. As is shown, the same variable was used in each of the trend curves for the abscissa (percent of units lost due to forgetting) which is that portion of the learning lost due to the retrogression that takes place during the interval of the production break. For example, if there were 12 units involved in the production sequence and the learning curve slope, 90 percent (Fig. 4), then the parametric value would be 75 percent, or 9 units lost due to the forgetting process.

There is also a requirement that trend curves monotonically increase or decrease in the same direction for utilization in construction of a prediction model. It was necessary to transform the data taken from the second parameter P_B by merely taking the reciprocal of the values taken from cuts of the trend curve (Fig. 3) to meet this requirement.

In the case of the third chosen parameter, learning curve slope, it was necessary to generate the data points by taking the example given with 12 predecessor units with a theoretical first unit (TFU) cost of $14.82 and computing the learning curve slopes for 95, 90, 85, 80, 75, and 70 percent. The learning values illustrated together with the learning curve slope differentials are shown in Figure 5. Calculations supporting the data shown in Figure 5 are illustrated in Appendix A. The trend curve for the third parameter P_C plotted from these data is shown in Figure 6.

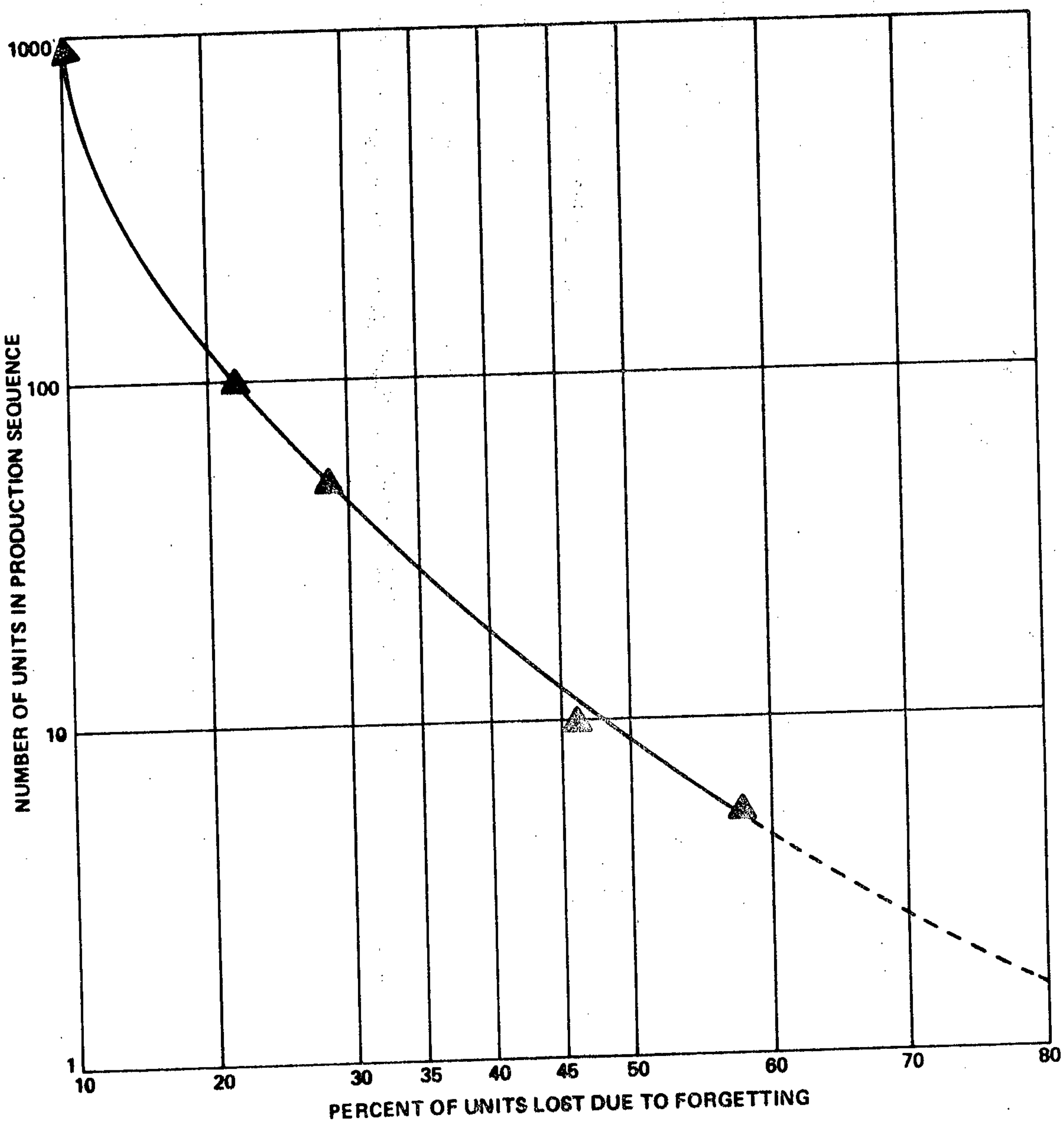


Figure 2. P_A trend curve.

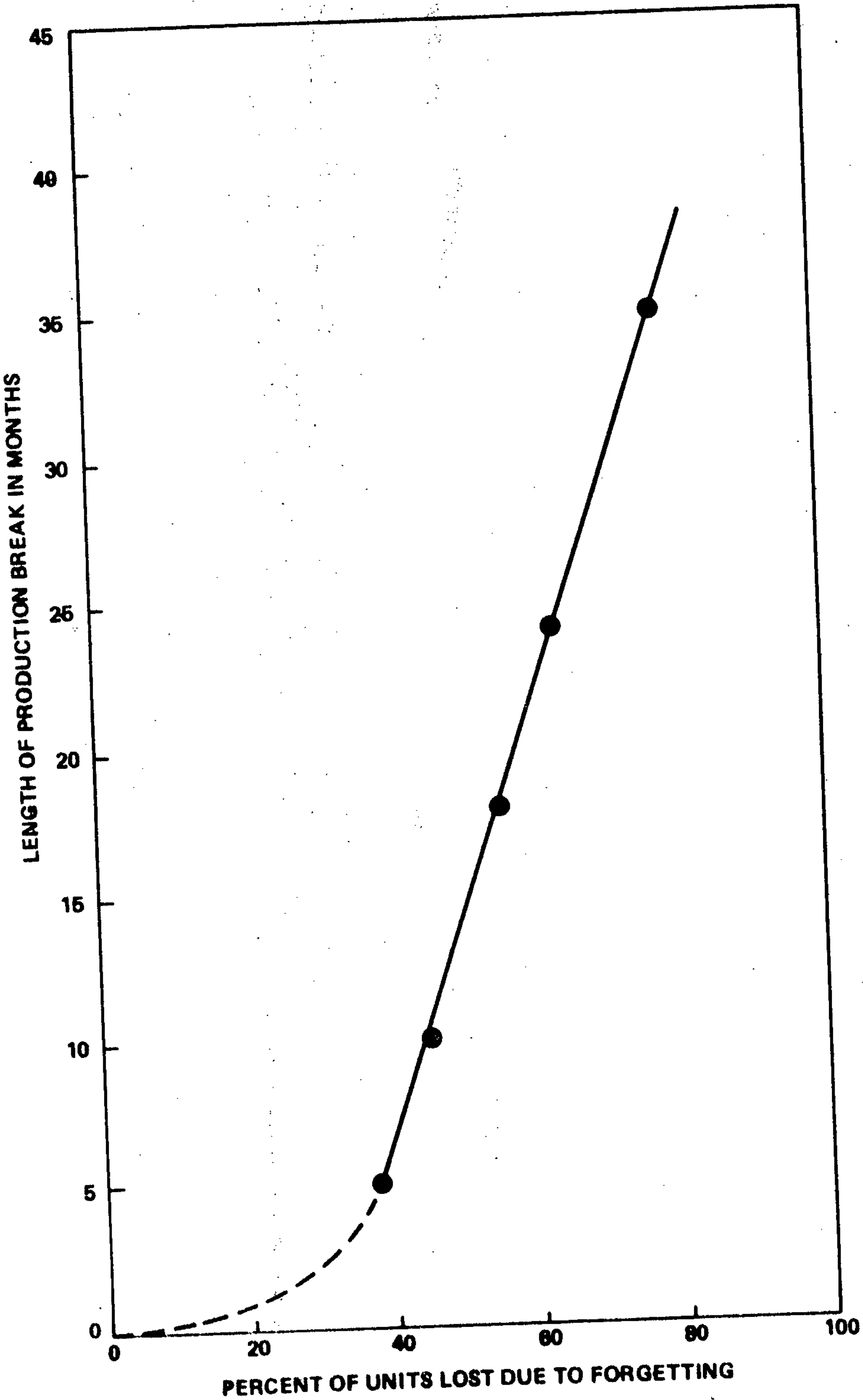


Figure 3. P_B trend curve.

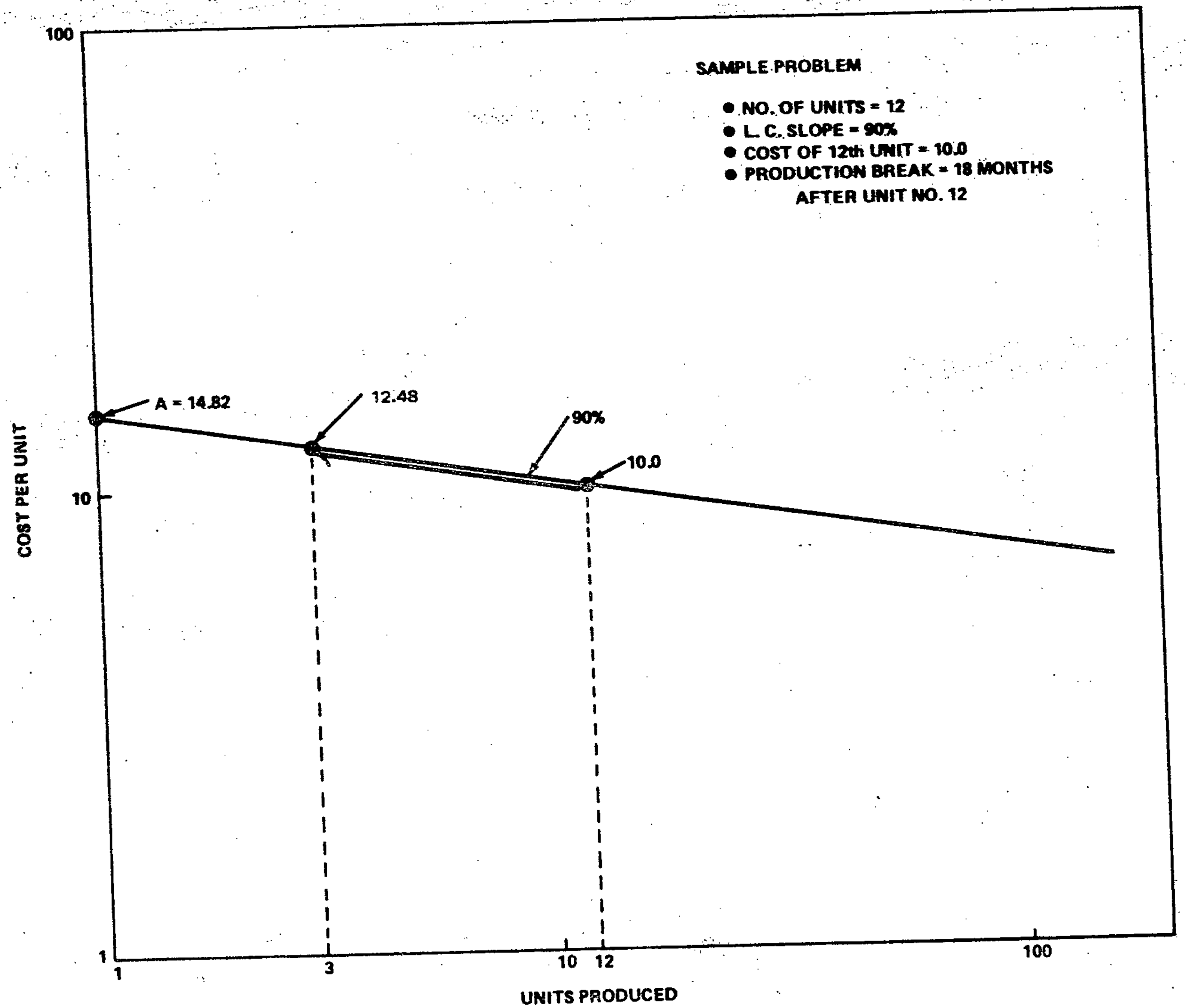
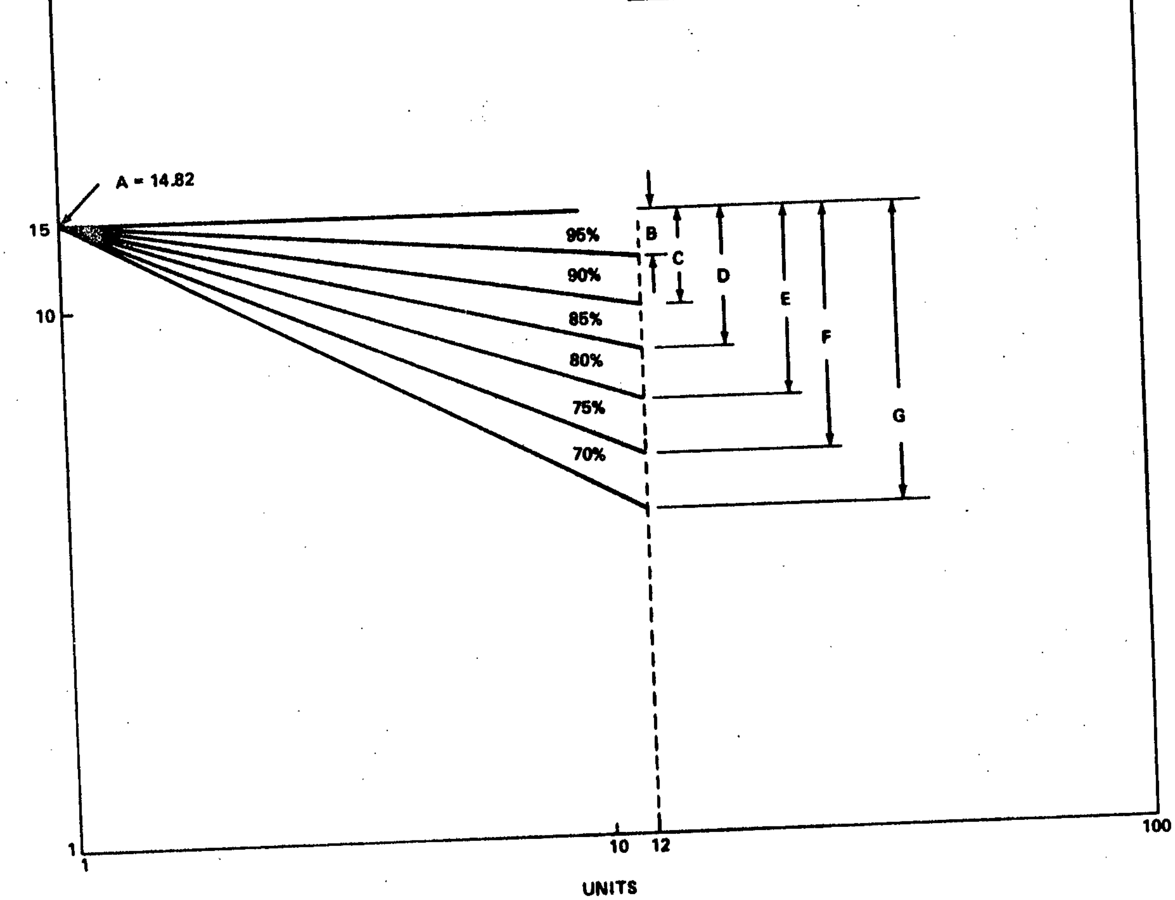


Figure 4. Learning curve.

* NO.	LEARNING VALUE	SLOPE	% LOSS
B	2.63288	95%	26.8
C	4.82246	90%	49
D	6.65982	85%	67.7
E	8.21137	80%	83.4
F	9.52689	75%	96.8
G	10.64372	70%	108



*SEE TREND CURVE FIG. NO. 6

Figure 5. Learning curves to show effect of slope on the quantity of learning.

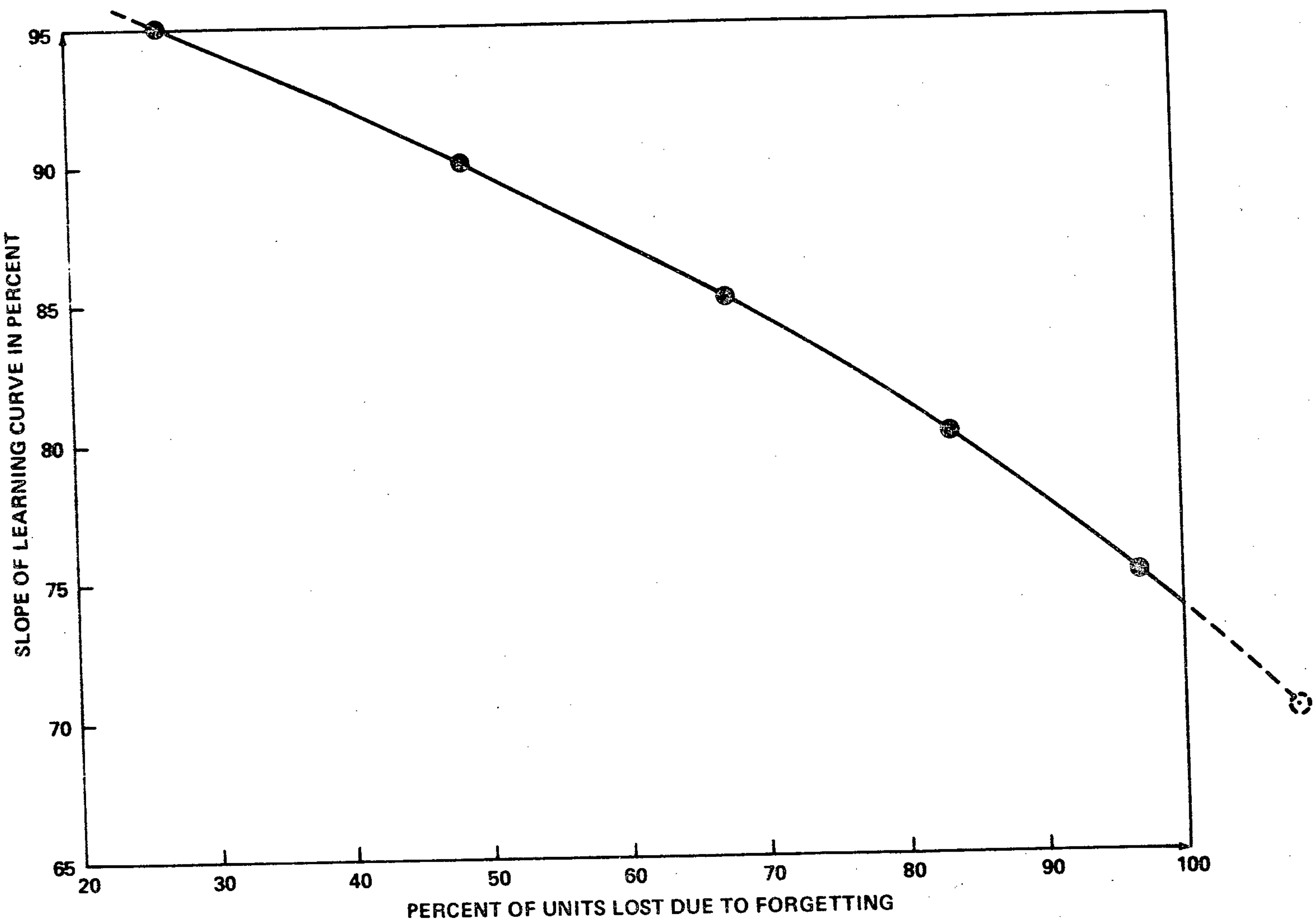


Figure 6. Trend curve, P_C.

B. Figure of Merit Computation

The time series multiplicative format is used to form the basis for the prediction model. Cuts are taken at regular intervals along the abscissa of the trend curves, from 35 to 80 percent. These values are used to compute the FOM for the first model as follows:

$$Q_{T1} = P_A \times P_B \ldots Pi \times Pj \quad . \tag{1}$$

The cuts have been collected from the trend curves for the two-parameter model in Table 1. These tabular values were used to plot a characteristic curve in Figure 7. This is accomplished by computing the FOM for the particular number of production units and length of time interval for the production break, and then entering the characteristic curve at the ordinate or FOM value.

The addition of a third parameter to the prediction model format was accomplished by use of the data developed for the learning curve slope. The relation for the FOM calculation then follows:

$$Q_{T2} = P_A \times P_B \times P_C \ldots Pi \times Pj \quad . \tag{2}$$

Cuts were taken again from the P_C trend curve and were displayed in the FOM table, Case II (Table 2). These FOM values were used to plot a characteristic curve representing the three parametric values embedded in a single FOM number. The curve is shown in Figure 8.

C. Prediction Models

Based on the foregoing analysis, two prediction models have evolved. These two models, Case I and Case II, are related by virtue of the fact that the first two parameters are common. The addition of the learning curve slope parameter to the Case II model makes it unique. The two models are as follows:

TABLE 1. FIGURE OF MERIT TABLE, CASE I

Q_{TI}

CUT%	P_A	B	P_B	$P_A \times P_B$
35	26.3	3.6	27.777	731
36	24.0	3.9	25.641	615
38	20.5	5.0	20.0	410
40	17.5	7.0	14.286	250
41	16.0	7.8	12.821	205
42	15.0	8.5	11.765	176.5
43.5	13.2	9.5	10.526	139
45	11.6	10.5	9.524	110.5
50	8.2	14.7	6.803	55.8
60	4.3	22.0	4.545	19.5
70	2.45	29.5	3.390	8.3
80	1.45	37.0	2.703	3.9

$Q_{T1} = P_A \times P_B \ldots P_i \times P_j$ = FOM OR

$Q_{T2} = P_A \times P_B \times P_C \ldots P_i \times P_j$ = FOM

NOTES

SAMPLE CALCULATION

$$P_B = 10^2 \times \frac{1}{B}$$

$$P_{B35} = 100/3.6 = \underline{27.777}$$

*SEE CHARACTERISTIC CURVE

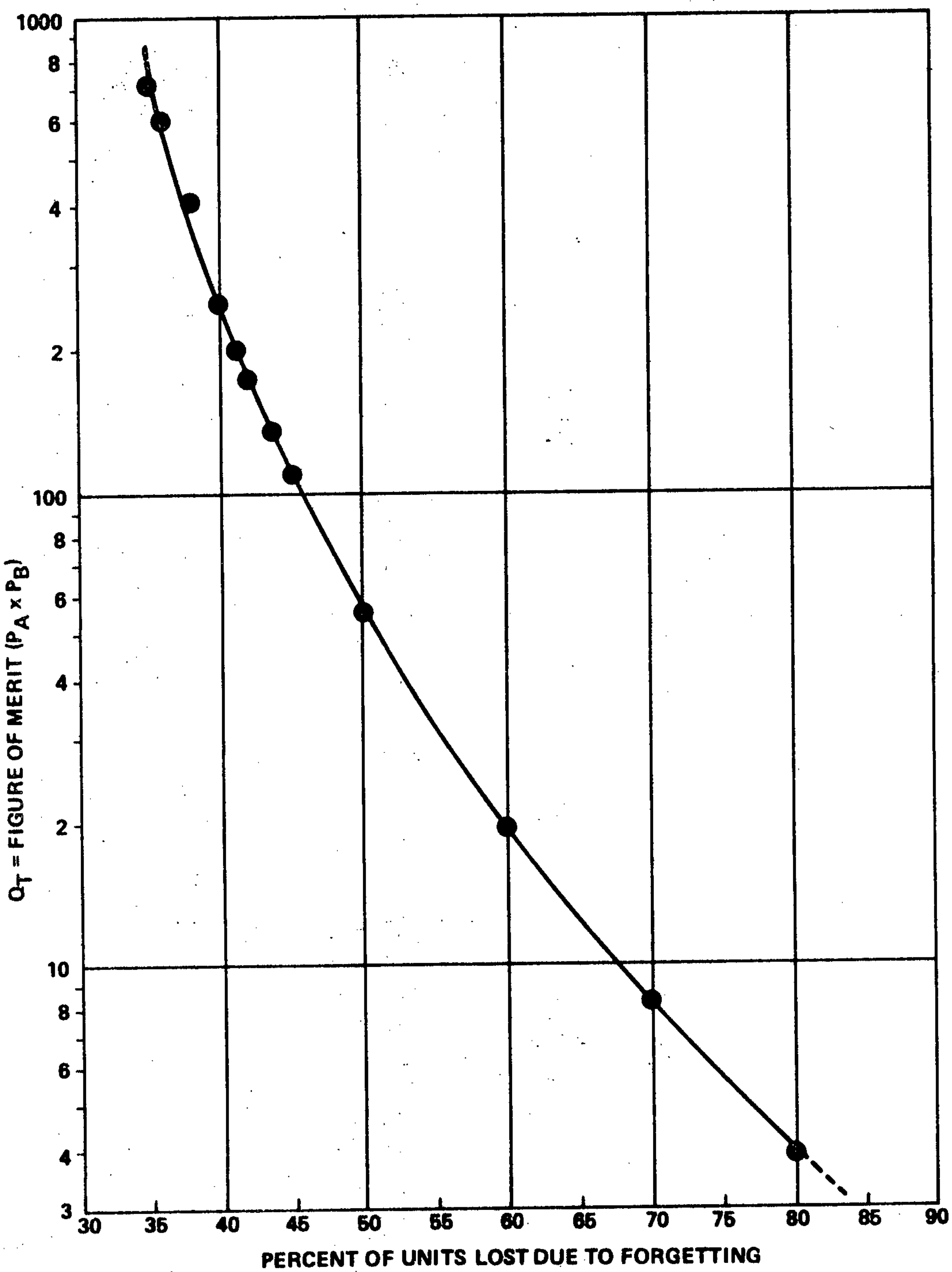


Figure 7. Characteristic curve, Case I.

TABLE 2. FIGURE OF MERIT TABLE, CASE II

QT_2

CUT %	Q_{TI}	P_C	$Q_{TI} \times P_C$
35	731	93.2	68,129
36	615	93	57,195
38	410	92.7	38,007
40	250	92.4	23,100
41	205	91.9	18,840
42	176.5	91.7	16,185
43.5	139	91.3	12,691
45	110.5	90.9	10,045
50	55.78	89.7	5,004
60	19.5	87.2	1,700
70	8.3	84.4	701
80	3.9	81.2	317

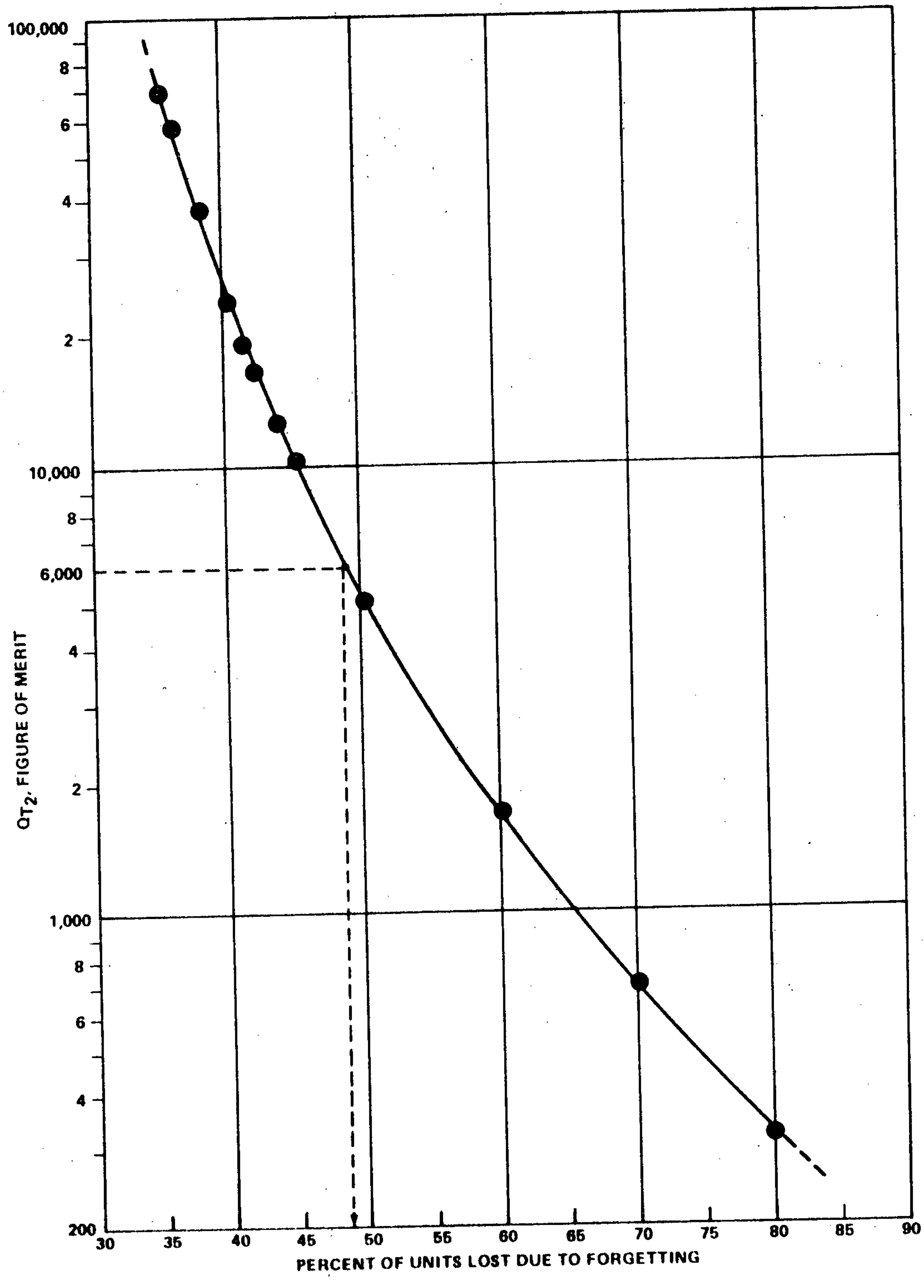


Figure 8. Characteristic curve, Case II.

$$Q_{T1} = P_A \times P_B \ldots\ldots \text{ Case I}$$

$$Q_{T2} = P_A \times P_B \times P_C \ldots\ldots \text{ Case II} \quad ,$$

where

P_A = number of units in production sequence

P_B = length of production break in months

P_C = slope of learning curve in percent

$Q_{T1}, Q_{T2} \approx$ FOM .

The computed values of FOM are used to interrogate the characteristic curve at the ordinate or FOM value. The output is then read from the abscissa, percent of units lost due to forgetting.

D. Application of Models to Sample Problems

Several illustrative examples for the learning loss of a production break are given in this section.

Example No. 1, Case I

Given:

P_A = 20 units, B = 12 months

$$Q_{T1} = P_A \times P_B \qquad P_B = 10^2 \times \frac{1}{B} = \frac{100}{12}$$

$$= (20)(8.3) \qquad P_B = \underline{8.3}$$

$$Q_{T1} \approx \underline{166.0}$$

from the characteristic curve of Figure 7, at Q_{T1} = 166, the learning loss is 42 percent.

Example No. 2, Case I

Given:

P_A = 12 units, B = 18 months

$$P_B = 10^2 \times \frac{1}{B}$$

$$= 100 \times \frac{1}{18}$$

$$P_B = \underline{5.555}$$

$$Q_{T1} = P_A \times P_B$$

$$= (12)(5.555)$$

$$Q_{T1} \cong \underline{67}$$

from the characteristic curve of Figure 7, at $Q_{T1} = 67$, the learning loss is 49 percent.

Example No. 3, Case II

Given:

P_A = 20 unit, B = 10 months

P_C = 80%

$$P_B = 10^2 \times \frac{1}{B} = 100 \times \frac{1}{10}$$

$$P_B = \underline{10.0}$$

$$Q_{T2} = P_A \times P_B \times P_C$$

$$= (20) \times (10) \times (80)$$

$$Q_{T2} \cong \underline{16\ 000}$$

from the characteristic curve of Figure 8, at Q_{T2} = 16 000, the learning loss is 42.5 or 43 percent.

Example No. 4, Case II

Given:

P_A = 12 units, B = 18 months

$P_C = 90\%$ $\qquad P_B = 10^2 \times \frac{1}{18} = 100 \times \frac{1}{18}$

$P_B = 5.555$

$Q_{T2} = P_A \times P_B \times P_C$

$= (12)(5.555)(90)$

$Q_{T2} \approx \underline{6000}$

from the characteristic curve of Figure 8, at $Q_{T2} \cong 6000$, the learning loss is 48.5 or 49 percent.

To determine the extent of the retrogression in learning, the following computations are in order:

TFU or A for a 90% curve $\cong$	14.82
Less cost for the 12th unit $\cong$	10.00
Learning on the 12 units	4.82

Learning value lost = Learning value × % learning lost.

$\cong 4.82 \times 0.485$

$\cong$ 2.3377 learning lost.

Learning retained = TFU — learning lost.

LR $\cong 14.82 - 2.3377$

LR $\cong \underline{12.4823}$

Conclusion

Therefore the forgetting loss in problem example no. 4 retrogresses back to the third unit of the production sequence (Fig. 4).

IV. CONCLUSIONS AND RECOMMENDATIONS

The example for the study of the production break was the Shuttle Solid Rocket Booster (SRB) project. The current program plan calls for an 18 - months production break after completing 12 research and development units of the SRB. Based on the present plan, the overall program for the SRB calls for the various subsystems to be treated separately. That is, there is a principal contractor for each prime subsystem element (e.g., structures, thrust vector control, propulsion, etc.). It also follows that there will be a separate learning/cost improvement curve for each of these separate contracts.

Appendix B, Memo for Record, dated April 11, 1977, defines the problem of computing the TFU cost for the SRB project. Also the question is raised as to whether the costs during a production break are of the recurring or nonrecurring type for the production gap. The conclusion is reached that all of the costs attributable to the production break/gap are of the nonrecurring type. That is, the costs are of a "one time only" category occurring only once in the life of a program.

Also, as previously mentioned, the model building process was affected by the availability of suitable data points. In spite of this, a model was eventually determined which can be used to predict the learning loss during a production break/gap. The model (Case II) is based on the following prime parameters: (a) number of units in production sequence, (b) length of production break in months, and (c) slope of learning curve in percent. Each of these parameters is plotted as the ordinate with a common abscissa of the percent of units lost due to forgetting. Each of these parameters was plotted as trend curves and was included in the text. To clarify the application process of the model, sample problems were illustrated to show the actual application to various hypothetical production break situations.

In spite of the obvious limitations of the models as presented, there are no apparent reasons why the described methodology could not be used for a general solution to the production break problem.

The production break problem is a contractor-oriented problem and the vast source of information remains with the people who actually build the production units. The acquisition of suitable data points might involve information which is considered proprietary.

APPENDIX A

CALCULATIONS FOR GENERATION OF DATA FOR TREND CURVE PARAMETER, P_C

As illustrated in Figure 5, the learning values have been calculated for learning curve slope values of 95, 90, 85, 80, 75, and 70 percent. It also follows that the percent of learning lost during a production break was computed for each of these values. These percent loss values have been indicated by the table shown in Figure 5. A sample computation is given as follows:

Given:

TFU or $A = 14.82246$

$X = 12$, $\text{LOG } X = 1.079181$

Slope $= 85\%$, $b = 0.24008$

To Find: Y_2

$$Y_2 = AX^{-b}$$

$$\text{Log } Y_2 = \text{Log } A - b \text{ Log } X$$

$$\text{Log } Y_2 = 1.1709206 - (0.24008)(1.079181)$$

$$\text{Log } Y_2 = 1.1709206 - 0.2590897$$

$$\text{Log } Y_2 = 0.9118309$$

$$Y_2 = \underline{8.162639}$$

Then if $A = 14.822460$

Less Y_2 $- \underline{8.162639}$

Learning Value $= \underline{6.659821}$

(For 12 units, 85% Slope)

APPENDIX B

MEMO FOR RECORD

National Aeronautics and
Space Administration

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama
35812

NASA

Reply to Attn of EL02

April 11, 1977

TO: MEMO FOR RECORD

FROM: L. M. Delionback

SUBJECT: Computation of TFU for the Operations or Production Run for SRB Program

Introduction: In discussion with the Shuttle Projects Office, it was explained that the way the production gap (18 months) was accounted for was to back up the learning curve to the point where 1/2 of the learning (cost) was reached during the production of the DDT&E flight units. This point was approximately the third unit of the DDT&E group. This approach will be used for each of the subsystems in question. Also, the particular learning curve type for each subsystem in question, whether Wright or Crawford, will be used for appropriate projections of cost for the production run.

Based on the assumption that the contract value for Deliverable Hardware for each subsystem represents the "Cumulative Total Cost" in learning curve iterations,* the initial unit cost for DDT&E will be computed by dividing the Cumulative Total Cost by the cumulative total factor for the particular number of units and Learning Curve Slope. This will yield the cost for the initial unit of the DDT&E run. Once this value has been computed, any value along the learning curve slope (specified by the contractor) can be determined. With the previous assumption that unit #3 represents approximately the loss of 1/2 of the overall learning in the production of the DDT&E units, it will represent the production cost of the TFU for the production run. The final unit cost may be determined in a similar manner by coming down the learning curve to the appropriate unit number.

*Source Rod Moak, Shuttle Project Office.

The question concerning recurring versus non-recurring costs quite naturally comes up relative to any additional charges to the program. The additional costs which are attributed to the 18 month production gap should be treated as non-recurring costs. These charges represent cost values which are "one-of-a-kind" expenditures to the program, and will not be repeated again for the foreseeable remainder of the current program. Therefore, such costs should be handled as additional charges to the non-recurring line items. Whatever the program effort requires to restore the productive capability back to its original posture on the learning curve (slope is contractor supplied) may be included in this delta cost. To illustrate this approach a hypothetical example will be given to show the methodology.

Example:

Assume:
1. Total Deliverable Hardware Cost = $120M
2. Crawford Learning Curve Slope = 90%
3. DDT&E Units = 12

To Find: Penalty costs for 18 months production gap.

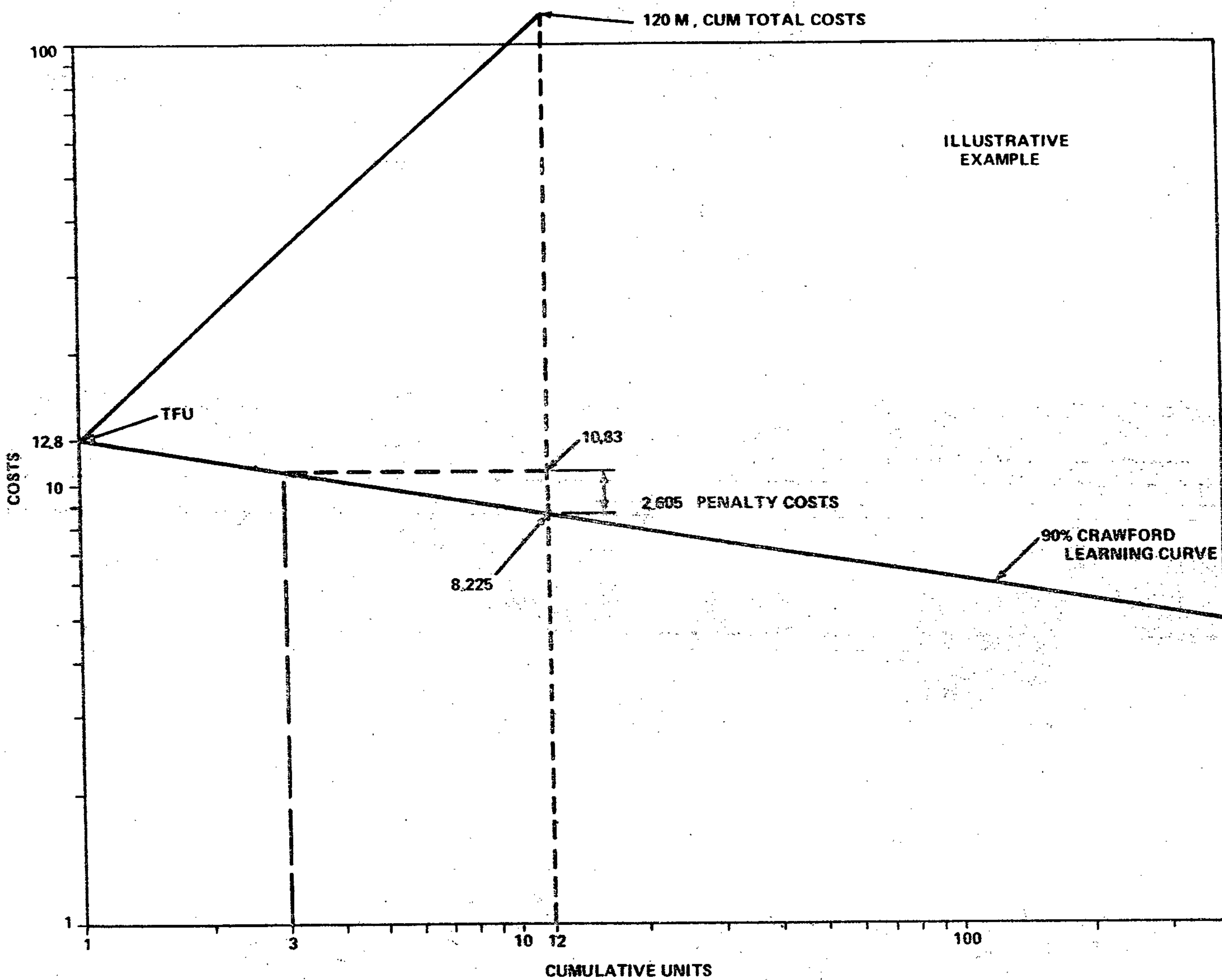
See attached learning curve plot.

L. M. Delionback

L. M. Delionback, PhD

1 Enclosure

cc:
EL02/R. D. Stewart


120 M , CUM TOTAL COSTS
ILLUSTRATIVE EXAMPLE
TFU
10.83
2.605 PENALTY COSTS
8.225
90% CRAWFORD LEARNING CURVE
COSTS
100
12.8
10
1
3
10
12
100
CUMULATIVE UNITS

Enclosure 1

REFERENCES

1. Carlson, John G., and Rowe, Alan J.: How Much Does Forgetting Cost? University of Southern California, Los Angeles, California, Journal of Industrial Engineering, vol. 8, no. 9, September 1976.

2. Cochran, E. B.: Planning Production Costs: Using the Improvement Curve. Chandler Publishing Co., 1968, pp. 381-382.

3. Gauger, Joe: Determination of the Cost Impact of a Gap in Production Schedule. The Boeing Company, Document No. D180-18829-1, June 1975, p. 10.1.

4. The Boeing Company: S-1C Cost Report High Rate Production. Michoud, December 1970, p. 10.

5. Anderlohr, George: What Production Breaks Cost. Vol. 1, no. 9, September 1969.

6. Pichon, Allen A. Jr.: The Development of a Predictive Model for First Unit Costs Following Breaks in Production. USAF, Wright-Patterson, Ohio, Masters Thesis, August 1974.

7. Yamane, Taro: Statistics, An Introductory Analysis. Harper & Row, Publishers, New York, 1964, pp. 350-367.

8. Delionback, Leon M.: Memo for record, Computation of TFU for the Operations or Production Run for SRB Program. NASA Internal Correspondence, April 11, 1977.

9. Delionback, Leon M.: Manufacturing Complexity Analysis. NASA TM X-73373, February 1977.

10. Delionback, Leon M.: Guidelines for Application of Learning/ Cost Improvement Curves. NASA TM X-64968, October 1975.

11. Delionback, Leon M.: A Design-Oriented Prediction Model for Learning Rates of Individual Mechanical Assembly Tasks. Doctoral Dissertation, Oklahoma State University, Stillwater, Oklahoma, May 1972.

BIBLIOGRAPHY

Benjamin, Jack R.: Probability, Statistics, and Decision for Civil Engineers. McGraw-Hill Book Co., New York, 1970.

Box, George E. P.: Time Series Analysis, Forecasting and Control. Holden-Day, Inc., 1970.

Burns, Jewel Ralph: A Comparison of Two Methods for Predicting Loss of Learning Due to a Break in Production. DARCOM-ITC-02-08-76-107, Darcom Intern Training Center, Red River Army Depot, Texarkana, Texas, March 1976.

Floyd, A. L., and James R. Bright, ed.: Technological Forecasting for Industry and Government. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1968.

Hartmeyer, Fred C.: Electronics Industry Cost Estimating Data. Ronald Press Co., New York, 1964.

Kirby, Robert M.: A Comparison of Short and Medium Range Statistical Forecasting Methods. Management Science, vol. 13, no. 4, 1966.

Ilderton, Robert Blair: Methods of Fitting Learning Curves to Lot Data Based on Assumptions and Techniques of Regression Analysis. Masters Thesis, George Washington University, August 1970.

Isenson, Raymond S.: Technological Forecasting in Perspective. Management Science, vol. 13, no. 2, October 1966.

McDonald, Paul: Improvement Curves. Procurement Associates, Covina, California, 1973.

Morgan, R.: Effect of Interrupted Production on the Learning Curve. Litton Systems, Internal Correspondence, File No. RCM:413:164, June 24, 1969.

Thompson, D. C.: Decision Modeling: the Art of Scientific Guessing. Machine Design, November 12, 1970.